TITLE: When Theory Becomes Practice: Integrating Scientific Disciplines for Tactical Mission Analysis and Systems Development

TITLE: Usability of Information in Battle Management Operations [1'Exploitation de l'information dans les operations de gestion du champ de bataille]

When Theory Becomes Practice: Integrating Scientific Disciplines for Tactical Mission Analysis and Systems Development

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The dynamics of tactical missions are of a specific nature. Determined and shrewd exploitation and control of their inherent real-time, safety-critical operational dynamics are vital for success in a wartime or disaster scenario. This paper describes research and development of theories, methods and tools for modeling, analysis and accident prevention in precarious time-critical air traffic control, process control, emergency response and military operations. We performed case studies, field studies, and experiments using a combined systems theory, Cognitive Systems Engineering and psychophysiology framework. We carried out Joint Tactical Cognitive Systems identification, modeling, and synthesis, and investigated inherent command, control, and intelligence activities. We found significant relations between workload, time pressure, cognitive complexity, and physiological stress responses.

Introduction

The Nature of Complex Dynamic Processes and Operations can be characterized as high-risk activities, where human and artificial team members together perform a task, which exacts extreme mobility, efficiency, agility and endurance. In emergency management, air traffic control and military operations mission performance relies increasingly on distributed systems (with many team-players, widely separated, forced to co-ordinate with one another) to attain high safety and effectiveness without risking excessive resource depletion. Commanders and operators will in the future be executing missions with operational and system characteristics that are highly dynamic and non-linear, i.e. small actions or decisions may have serious and irreversible consequences for the mission as a whole. In these kinds of activities decisions and actions are never isolated events. They occur in the context of:

- Stress effects.
- Uncertain evidence.
- Ambiguous information.
- Time pressure and time delays.
- High physical and mental workload.
- Goal conflicts (organizational and social factors).
- Minor actions that can trigger large consequences.
- Highly dynamic and sometimes chaotic environments.

Performing complex, high-risk, tactical operations requires support by highly capable management. High-capacity C^3I support is needed to facilitate omnidirectional, continuous of information flows from the chief executive level to the team-on-site levels. Sometimes individual operators and sensor systems must without delay be allowed to affect decisions and actions of a senior commander. This is beyond reach unless new, cutting-edge solutions can support the humans and systems engaged. The military community calls for ground-breaking approaches to demanding battle management problems. Analogous to this, the art and practice of command and control, tactics, techniques, procedures and training are forced to constantly and concurrently strive for perfection. However, as Rochlin (1997) and others have observed, the specific skills and properties that systems, managers and operators have to possess in order to yield optimal mission performance in such critical and uncertain situations are not easily identified, and hence, they are difficult to improve.

Our underlying principle was integration of well-established scientific disciplines into a pioneering research direction, *Action Control Theory,* a framework specifically composed to facilitate empirically based conceptual modeling of dynamic, complex tactical systems and processes and of their states and state transitions. The resulting models will be used for complex, multi-level human-machine systems design in the military, aviation and emergency response domains.

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The Action Control Theory Framework

Action Control Theory (ACT) is a composite theoretical structure, derived from advances in

I. Cognitive Systems Engineering (CSE).
II. Systems Theory, Control Theory and Cybernetics.
III. Decision Making in Complex Systems Control and Mission Command.
IV. Psychophysiology.

The four research constituting ACT have until now developed along separate paths of evolution. However, now it is time to investigate what they might offer when implemented in an integrated, cohesive and coordinated manner. Flach & Kuperman (1998) concluded that it is essential to develop a unified, proactive, CSE-based approach in research and systems design for future warfare environments. We agree, and hold a strong belief in the power of integrative research approaches:

- Built on solid classical and innovative theoretical work.
- Using comprehensive yet simple and robust conceptual and specific models of systems, tasks and missions.
- Supported by advanced experimental and measurement methods, and data analysis techniques.

Theoretical Constituent I: Cognitive Systems Engineering

The area of Cognitive Systems Engineering has grown steadily since the first significant contributions were published in the 1980s by Rasmussen (1983; 1986), who introduced the concept of skill-based, rule-based and knowledge-based behavior for modeling different levels of human performance. Endsley (1995) developed a comprehensive theory of individual operator, commander, and team situation awareness in dynamic systems. Danielsson & Ohlsson (1996) studied information needs and information quality in emergency management decision making. This work also applies to the military context. Woods & Roth (1988) made a comprehensive review of the CSE domain. Hollnagel & Woods (1983) made a significant contribution to this field by their definition of a *Cognitive System* (CS) as a Man-Machine System (MMS) whose behavior is goal-oriented, based on symbol manipulation and uses heuristic knowledge of its surrounding environment for guidance. A cognitive system operates using knowledge about itself and the environment to plan and modify its actions based on that knowledge. In complex systems this is indisputable. For example, in Command and Control (C^2) tasks in military missions a multitude of sensor systems, communication systems, training programs, personnel and procedures are all elements of the total operational system. Viewing this system as a cognitive system permits the integration of all existing control resources: operators and commanders, technological facilities, doctrine, procedures and training into a coordinated system that can achieve a mission safely and efficiently. The use of CSE to model, analyze, and describe such systems performing hazardous, real time, high-stake activities is a powerful approach, given a sufficient understanding by the investigator of the interdependencies and linkages between other research areas and the CSE field.

Theoretical Constituent II: Dynamic Systems Theory, Control Theory and Cybernetics

By the term *dynamic system* is meant an object, driven by external input signals $u(t)$ for every t and as a response produces a set of output signals $y(t)$ for every t. From the work of Ashby (1956), Brehmer (1992) and many others it is well known that most complex systems have *real-time, dynamic properties*; the system output at a given time is not only dependent of the input value at this specific time, but also on earlier input values, and that a good regulator of a system has to implement a model of the system that is to be controlled. Put otherwise, Ashby's law of requisite variety (Ashby, 1956), states that the variety of a controller of a dynamic system has to be equal to or greater than the variety of the system itself.

An approach based on control theory and dynamic systems can facilitate structuring and understanding of the command and control problem. The mathematical stringency and powerful formalism of control theory makes it possible to describe and treat systems as diverse as technical, organizational, economic and biological dynamic systems in basically the same manner: as processes, or clusters of processes, with a built-in adherent or assigned control system. The concepts of control theory can be used as metaphors in research on decision making, especially in multiple-player, dynamic contexts. The notion that decision making constitutes the regulatory function in command and control processes (Orhaug, 1995) strongly supports the control theory approach. This notion also supports the fact that the hierarchical command structures of military and emergency response organizations are strongly coupled to both centralized and distributed decision making principles (Brehmer, 1988). Annett (1997) used control theory to investigate team skills. This hints at the use of a control theory framework for analysis and evaluation of command and control in tactical operations. Four fundamental requirements must be met (Conant & Ashby, 1970, Glad & Ljung, 1989 and Brehmer, 1992) if control theory is to be used in analysis and synthesis of dynamic systems:

1. There must be a goal (*the goal condition*).
2. It must be possible to ascertain the state of the system (*the observability condition*).
3. It must be possible to affect the state of the system (*the controllability condition*).
4. There must be a model of the system (*the model condition*).

Controlling Joint Systems and Processes

The combined view of control theory in technical as well in behavioral domains is crucial for success in this research area. When a function is implemented at one level of abstraction, represented at a second level of abstraction and controlled at a third level of abstraction the requirement for timely and complete information varies accordingly. On the other hand, it is not important whether a function or mission is carried out by an operator or by an automated system under higher-order supervision, the operators and the supervisory controllers still need to maintain an *adequate situation understanding* – or situation awareness.

If reliable and timely observation and measurement of the system output is unfeasible, and situation understanding cannot be based on the information supplied by the system, it must be based on the current process knowledge and understanding of the situation. Operators and controllers must compensate by means of accurate system performance prediction. This prediction ability is based on the axiom that a cognitive system must be able to think ahead in time and anticipate the dynamics of the process. To accomplish this a cognitive system must solely rely on exact model knowledge of the system input's influence on the system output. This is normally referred to as *open-loop control*. Open-loop control can be a cumbersome and arduous task, especially when the system environment and the mission context is highly dynamic and the system process is unstable and non-linear, i.e. small changes or state transitions in the process can generate an unproportional, unpredictable or even chaotic system behavior. In some cases the disturbances can be measured. It is then possible to almost entirely eliminate the influence of those disturbances by using *feedforward control*. However, this requires extremely good system knowledge of the process that we wish to control. Feedforward control is also sensitive to variability in the system dynamics. The main advantage of feedforward control is the possibility to counteract the effects of disturbances before they are visible as an undesired deviation from the reference. Control theory has proven that although feedforward control can be considered the perfect mode of control, it is often only achievable for a limited amount of time due to *model error* caused by, among other things, the time-constants of the process. However, if the system output can be used to determine the system state, there is only a limited need for detailed knowledge of system dynamics, and *feedback control* can be executed. The necessary adjustments and updates of the controller's internal system model can be made by constantly measuring the deviation of the system output from the reference value. The joint cognitive system is unstable without feedback, and thereby feedback will be needed to correct deviations and compensate for the incompleteness and inadequacy of the internal system model. Reason (1997) emphasized the importance of balance between feedback (reactive) control and feedforward (proactive) control. This concept is crucial to achieve optimal C^2 performance in a tactical mission. Feedforward control is often combined with feedback control because of its practical reliability limitations.

Theoretical Constituent III: Decision Making in Complex Systems Control and Mission Command

Brehmer (1992) suggested the use of control theory as a framework for research in *distributed, dynamic decision making*. The conventional view of decision making, supported by normative theories, reduces decision making to selecting an appropriate action from a closed, pre-defined action set, and to resolution of conflicts of choice. As a consequence, the analysis of decision tasks focuses on the generation of alternatives and the evaluation of these alternatives as in Multi-Attribute Utility (MAU) analysis (Kleindorfer et al., 1993). Research in dynamic decision making has been based on analysis of several applied scenarios, e.g. military decision making, operator tasks in industrial processes, emergency management and intensive care (Brehmer, 1988; 1992). Two things were clarified in these analyses:

1. The decision making was never the primary task. It was always directed towards some goal.
2. The dynamic character of the assigned tasks became apparent in the study of the applied contexts.

These results are consistent with earlier descriptions by Edwards (1962), Rapoport (1975) and Hogarth (1981) of dynamic decision making, which Brehmer (1992) summarised as follows:

1. *A series of decisions is required to reach the goal.* To achieve and maintain control is a continuous activity requiring many decisions, each of which can be understood only in the context of the other decisions.
2. *The decisions are mutually dependent.* Later decisions are constrained by earlier decisions and, in turn, constrain those that come after them.
3. *The state of the decision problem changes*, both autonomously and as a consequence of the decision maker's actions.
4. *The decisions have to be made in real time.* This finding has several significant implications, and they are elaborated upon in the next section.

The real time properties of dynamic decision making cause special problems:

1. *Decision makers are not free to make decisions when they feel ready to do so.* Instead, the environment requires decisions and the decision maker, ready or not, have to make these decisions on demand. This causes stress in dynamic decision making tasks. In order to cope with this stress, decision makers have to develop strategies for control of the assigned dynamic tasks and for keeping their own workload at an acceptable level.
2. *Both the system that is to be controlled and the procedures and resources the decision maker uses*

to control the system have to be seen and treated as processes. Dynamic decision making tasks can be characterized as finding a way to use one process to control another process.
3. *The different time scales involved in dynamic decision making tasks have to be monitored and taken into consideration.* In most situations the active agents in a dynamic system, such as the directly involved operators and their closest commander or squad leader, operate in a time scale of seconds to minutes. Their commanders and their command and control systems operate in time scales of hours to days.

An application of this approach in studies of distributed decision making in dynamic environments such as fire fighting and rescue missions was described by Brehmer & Svenmarck (1995).

Naturalistic Approaches to Decision Making
Zachary & Ryder (1997) reviewed decision making research during the last decades and elaborated on the recent major paradigm shift in decision theory. The shift is from analytic, normative decision making procedures described in Kleindorfer et al. (1993) to Naturalistic Decision Making (NDM), developed and described by Klein (1993a; 1993b), Zsambok & Klein (1997) as well as by Klein & Woods (1993). NDM applies to many dynamic and potentially dangerous areas of activity such as military missions, air traffic control, fire fighting, emergency response and medical care. The essentials of this paradigm are condensed below:

- Human decision making should be studied in its natural context.
- The underlying task and situation of a problem is critical for successful framing.
- Actions and decisions are highly interrelated.
- Experts apply their experience and knowledge non-analytically by identifying and effecting the most appropriate action in an intuitive manner.

Cannon-Bowers et al. (1996) reviewed, commented, and related the NDM approach to the extensive research on Distributed and Dynamic Decision Making described above. They argued that this was how to overcome the limitations of the notions of the classic normative research paradigm in decision making. A fundamental element of NDM, the Recognition-Primed Decision (RPD) model, was presented in detail in Klein (1993a) and was applied to complex command and control environments in Kaempf et al. (1996).

Tactical Team Decision Making
Tactical decision making teams in the modern warfare environment were faced with situations characterised by rapidly unfolding events, multiple plausible hypotheses, high information ambiguity, severe time pressure, and serious consequences for errors (Cannon-Bowers et al., 1995). There were also cases when geographical separation or other forms of distributed environments in which the teams operate impose additional difficulties Brehmer (1991). To be able to adapt to these situations, team members must co-ordinate their actions so that they can gather, process, integrate, and communicate information timely and effectively. This is particularly true of complex systems where it is difficult to assess performance with a single correct answer, or in situations where several individual decision makers who must interact as a team.

Theoretical Constituent IV: Psychophysiology
Within joint cognitive systems performing complex, high-risk military and emergency response missions there is a fundamental and profound connection between human operator physiological stress response and discrepancies between expectancies and experiences. The stress response is an warning of an homeostatic imbalance occurring (Levine and Ursin, 1991). This implies that the concept of *model error* from control theory once again can be applied. The stress response is also mobilizing physiological resources to improve performance, which is regarded as a positive and desirable warning response. The Cognitive Activation Theory of Stress (CATS) describes the phases of the stress response as an alarm occurring within a complex cognitive system with feedback, feedforward and control loops, no less but no more complicated than any other of the body's self-regulated systems (Eriksen et al., 1999). The time dimension of stress responses must be accounted for very carefully.

Models Derived from Action Control Theory

Tactical Joint Cognitive Systems
The point of departure in our ACT-based systems modeling endeavor was the Tactical Joint Cognitive System (TJCS), as the system

- To which a mission is assigned.
- To which the operational command of the mission is commissioned.
- To which the responsibility for effecting the mission is authorized.
- To which the resources needed for performing the mission are allocated.

A Tactical Joint Cognitive System is an aggregate of one or several instances of four principal sub-system classes:

1. *Technological Systems*, for example vehicles, intelligence acquisition systems, communication systems, sensor systems, life support systems, including the system operators.
2. *Command and Control Systems*, consisting of an information exchange and command framework, built up by technological systems and decision makers.

3. *Support Systems*, comprising staff functions, logistic functions, decision support functions, organizational structures, and other kinds of service support.
4. *Tactical Teams*, composed and defined according to (Salas et al., 1992):

"Two or more people who interact, dynamically, interdependently, and adaptively toward a common and valued goal/objective/mission, who have been assigned specific roles or functions to perform, and who have a limited life-span of membership."

The concepts of a Tactical Joint Cognitive System are depicted in Figure 1.

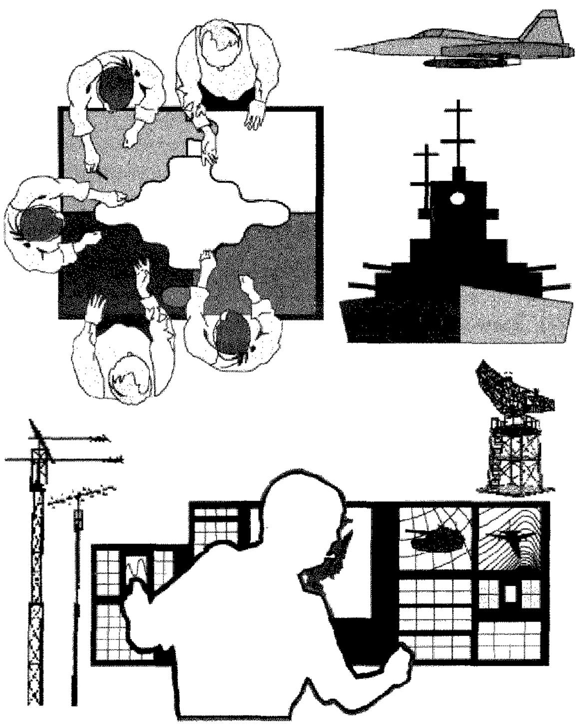

Figure 1. The *Tactical Joint Cognitive System.*

Another important aspect is how the actual mission affects team performance. Serfaty & Entin (1997) drew the following conclusions concerning the properties and abilities of teams successfully performing tactical, hazardous operations:

- The team structure adapts to changes in the task environment.
- The team maintains open and flexible communication lines. This is important in situations where lower levels in a command hierarchy have access to critical information not available to the higher command levels.
- Team members are extremely sensitive to the workload and performance of other members in high-tempo situations.

Tactical Action Control Models

We then turn our attention to the Tactical Action COntrol Model (TACOM, Worm, 2000c), as illustrated in Figure 2.

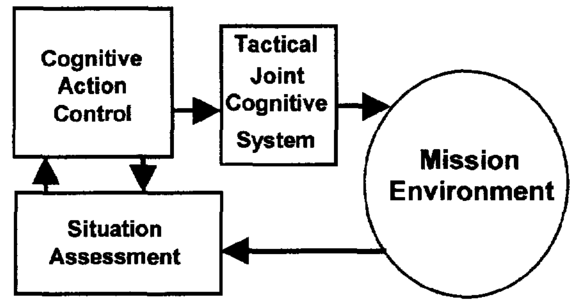

Figure 2. *The Tactical Action COntrol Model (TACOM).*

The principal components of the TACOM are the Mission Environment, the Tactical Joint Cognitive System, the Situation Assessment function, and the Cognitive Action Control function, derived primarily from the work of Brehmer (1988; 1992), Klein (1993a; 1993b) and Worm, 1998c.

Mission Execution and Control Models

The next step is integration of these concepts into a Mission Execution and Control Model (MECOM), illustrated in Figure 3. The MECOM consists of one or several TACOMs extended with control theoretic components, to handle system disturbances, model error, and to allow an adaptive and balanced mix of feedforward and feedback control.

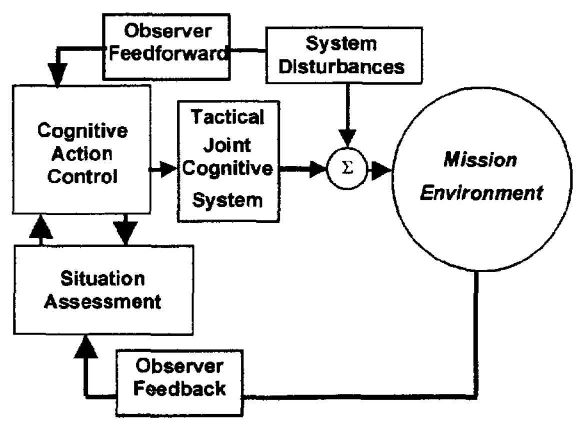

Figure 3. *The Mission Execution and COntrol Model (MECOM). This is a simplified version of the full model for greater clarity and for editorial reasons. The full model is depicted in Worm (2000b).*

Model Combination and Aggregation

The last step in the model formation process is combining and aggregation of several MECOMs into unilevel and multilevel MECOMs, respectively, as presented in Figure 4.

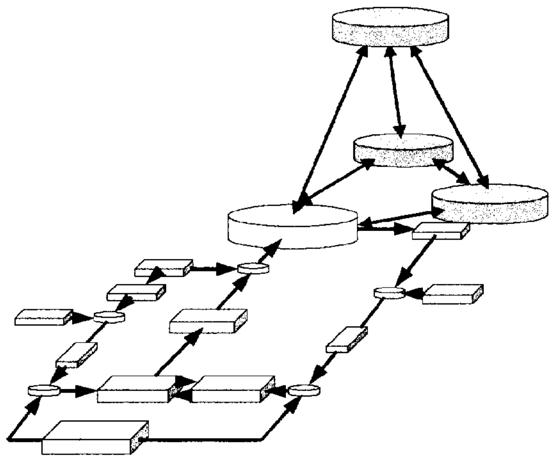

Figure 4. A simplified example of a MULTI-level Mission Execution and COntrol Model (MULTI-MECOM).

Methods: The TRIDENT project

In earlier publications (Worm, 1998b; 1999b; 1999c) we have reported on the progress of the *Tactical Real-time Interaction in Distributed EnvironmeNTs (TRIDENT)* project, aimed at developing a coherent and straightforward package of methods and techniques for man-machine systems analysis in the setting of tactical mission scenarios. The components of TRIDENT are:

- Using the Action Control Theory (ACT) Framework for conceptual modeling of dynamic, complex tactical systems and processes, of their states and state transitions.
- Identification of mission and unit state variables, and of action control and decision making mechanisms for process regulation (Worm, 1998a; 1998b).
- Mission Efficiency Analysis (Worm et al., 1998; Worm, 1999a) of fully manned and equipped units executing full-scale tactical missions in an authentic environment.
- Measuring information distribution and communication effectiveness (Worm, 1998b).
- Measuring workload by means of the NASA Task Load Index (Hart & Staveland, 1988).
- Assessing team member psychosocial mood by means of the Mood Adjective CheckList (MACL, Sjöberg et al., 1979).
- Assessing situation awareness (Endsley, 1995) as a function of mission-critical information complexity (Svensson et al., 1993)
- Measuring level and mode of cognitive, context-dependant control of the team members, and identifying what decision strategies were utilized by the team and team members.
- Applying reliability and error analysis methods for investigating failure causes both in retrospect and for prediction (Hollnagel, 1998).
- Validating identified constructs and measuring their influence using advanced data analytic procedures.

Numerous battle management and emergency response studies have been carried out in which we used every opportunity to test, refine and augment the modeling, measurement, data collection and analysis concepts of TRIDENT. Implementing our ideas for tactical mission analysis in potentially dangerous, stressful and cognitively complex environments showed to be very effective.

Using the TRIDENT concepts for analysis and evaluation on aggregated system levels has so far been very rewarding, with high acceptance among the subjects; trained and skilled professionals performing their daily tasks in their accustomed work environment. However, we have also experienced some critique. It is occasionally claimed that reliability and validity of subjective workload ratings are insufficient. For that reason we considered incorporating a measure of workload and stress which is commonly accepted in the scientific community. We considered hormonal response measures, inspired by the results of Svensson et al. (1993), who studied workload and performance in military aviation, Zeier, (1994) who studied workload and stress reactions in air traffic controllers, and Holmboe et al. (1975), who studied military personnel performing exhausting battle training.

We designed a study in order to elucidate to what extent hormonal physiological stress indications are linked to the rating, observation and data collection methods normally used in TRIDENT to assess workload and tactical performance. The study is described in Worm (2000a), and will be further elaborated upon in a coming doctoral thesis by this author.

Preliminary Results

The main causes of mission failure were information interpretation and distribution failures, due to:

- Slow organizational response.
- Ambiguous, missing or insufficiently disseminated, communicated and presented information.
- Equipment malfunction, e.g. power failure or projectile/missile impact.
- Personal factors: inexperience, lack of team training etc.

Our empirical results through the four-year project life suggest three potentially significant mechanisms influencing how the team is able to execute mission control, which consequently also influences mission efficiency:

1. Time-dependant filtering functions like defense and coping mechanisms according to the cognitive Activation Theory of Stress (Eriksen et al.; 1999, Levine & Ursin, 1991).
2. Dependence on individual mission task requirements (Worm, 2000c).
3. Balance between feedforward and feedback in mission-critical action control (Reason, 1997; Worm, 2000b).

Our theoretical achievements were a complicated and arduous venture, in that we have constantly striven for empirical evidence. Nevertheless we feel that we are approaching a scientific breakthrough. We argue that the ACT / TRIDENT approach will facilitate

1. Identifying limiting factors of a specific individual, unit, system, procedure or mission.
2. Assessing the magnitude of influence of these factors on overall tactical performance.
3. Proposing measures to support, control and improve insufficient capabilities and contribute to successful accomplishment of future missions.

FUTURE WORK

We have for a number of years struggled towards building a foundation for analysis and evaluation of high-stake, life-threatening tactical missions in various work contexts. Although earlier results indicate that we have reached a workable, reliable and valid result, the question is still if our findings are generally applicable. After preliminary analysis of the study reported on in this paper, we contend that studying individuals is a effective, reliable and valid way to probe the function and efficiency of an organization, performing complex tasks in an ever changing mission environment. We will continue to work with the data collected in this and earlier studies, and use the results from the scenarios analyzed to tune and adjust the theory, models and methods in order to obtain a coherent and cohesive framework for human-machine systems analysis of tactical mission settings and scenarios. We will also develop computerized versions of the test instruments, if possible with built-in tools for data analysis and graphical presentation, so that researchers and investigators not familiar with the background and early history of this project can benefit in their own work from our achievements.

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